

Eastern
Economy
Edition

Fundamentals of Compressible Fluid Dynamics



P. Balachandran



Contents

Preface

xv

1. FUNDAMENTAL PRINCIPLES

1-15

- 1.1 Introduction 1
- 1.2 Definition of a Fluid 2
- 1.3 Compressibility of Fluids 2
- 1.4 The Continuum Approach and the Molecular Approach 3
- 1.5 Properties of the Continuum 4
 - 1.5.1 Density at a Point in a Continuum 4
 - 1.5.2 Stress at a Point 5
 - 1.5.3 Velocity at a Point 5
- 1.6 System and Control Volume 6
- 1.7 Concepts and Definitions in Thermodynamics 6
 - 1.7.1 Thermodynamic Property 6
 - 1.7.2 Thermodynamic Process and Cycle 7
 - 1.7.3 Thermodynamic Equilibrium 7
- 1.8 Energy 7
 - 1.8.1 Stored Energy 7
 - 1.8.2 Energy in Transition 8
- 1.9 Laws of Thermodynamics 8
 - 1.9.1 Zeroth Law of Thermodynamics 8
 - 1.9.2 First Law of Thermodynamics 9
 - 1.9.3 Second Law of Thermodynamics 10
 - 1.9.4 Entropy 10
- 1.10 Perfect Gas 11
 - 1.10.1 Equation of State 11
 - 1.10.2 Change in Entropy in a Perfect Gas 12
 - 1.10.3 Isentropic Process 13
- Review Questions* 13

2. CONSERVATION LAWS FOR COMPRESSIBLE FLOW

16-37

- 2.1 Introduction 16
- 2.2 Extensive and Intensive Properties 16
- 2.3 Conservation of Mass and Continuity Equation 17
 - 2.3.1 Conservation of Mass for a System 17
 - 2.3.2 Conservation of Mass for Control Volume 18

2.3.3	Integral Form of Continuity Equation	20
2.3.4	One-Dimensional Differential Form of Continuity Equation	21
2.4	Conservation of Momentum and Momentum Equation	22
2.4.1	Conservation of Momentum for a System	22
2.4.2	Conservation of Momentum for Control Volume	23
2.4.3	Integral Form of Momentum Equation	25
2.4.4	One-Dimensional Differential Form of Momentum Equation	26
2.4.5	Eulers Equation	28
2.4.6	Bernoullis Equation	28
2.5	Conservation of Energy and Energy Equation	30
2.5.1	Conservation of Energy for a System	30
2.5.2	Conservation of Energy for a Control Volume	30
2.5.3	Integral Form of Energy Equation	33
2.5.4	Steady Flow Energy Equation	33
2.5.5	Energy Equation for a Non-flow Process	35
2.6	The Second Law of Thermodynamics and Entropy Equation	35
2.6.1	Second Law for a System	35
2.6.2	Second Law for a Control Volume	35
	<i>Review Questions</i>	36

3. CONCEPTS OF COMPRESSIBLE FLOW

38-85

3.1	Introduction	38
3.2	Velocity of Sound	38
3.2.1	General Equation for Velocity of Sound	39
3.2.2	Velocity of Sound in Incompressible Fluids	41
3.2.3	Velocity of Sound in Terms of Bulk Modulus of Elasticity	41
3.2.4	Velocity of Sound in a Perfect Gas	42
3.2.5	Effect of Molecular Weight	43
3.3	Mach Number and Its Significance	43
3.4	Incompressible, Subsonic and Supersonic Flows	44
3.5	Physical Difference between Various Flow Regimes	46
3.5.1	Pressure Field Created By a Point Disturbance	46
3.5.2	Mach Cone and Mach Angle	48
3.5.3	Flow Around a Wedge	49
3.5.4	Von Karman's Rules of Supersonic Flow	50
3.6	Concept of Stagnation Condition	51
3.6.1	Stagnation Enthalpy	52
3.6.2	Stagnation Temperature	53
3.6.3	Stagnation Pressure	54
3.6.4	Stagnation Density	54
3.6.5	Stagnation Velocity of Sound	55
3.6.6	Relation Connecting Stagnation and Static Properties	55
3.6.7	Entropy Change in Terms of Stagnation Properties	56
3.7	Kinetic Form of Steady Flow Energy Equation	58
3.7.1	Full Form of the Adiabatic Energy Equation	59
3.7.2	Prandtl Velocity Ellipse (Adiabatic Steady Flow Ellipse)	59

3.8	Reference Speeds of Compressible Flow	60
3.8.1	Critical Speed of Sound	60
3.8.2	Stagnation Speed of Sound	61
3.8.3	Maximum Isentropic Speed	61
3.8.4	Reference Mach Number M^*	62
3.8.5	Dimensionless Velocity V/a_0	64
3.8.6	Crocco Number	64
3.9	Stream Thrust and the Impulse Function	65
3.10	Effect of Compressibility on Dynamic Properties	66
3.10.1	Dynamic Pressure	66
3.10.2	Flow Compressibility Factor	68
3.10.3	Pressure Coefficient of Airfoil	68
3.11	Steady One-Dimensional Compressible Flow of Perfect Gas	69
3.12	Simple Flows	70
	<i>Illustrative Examples</i>	71
	<i>Review Questions</i>	83
	<i>Problems</i>	84

4. ISENTROPIC FLOW

86-135

4.1	Introduction	86
4.2	Governing Equations	86
4.2.1	Isentropic Process on Mollier Diagram	88
4.2.2	Flow Expansion and Compression	90
4.2.3	Performance Curves	90
4.3	Effect of Area Variation	91
4.3.1	Shape of Nozzle	93
4.3.2	Shape of Diffuser	94
4.3.3	Choking	95
4.4	Reference States and Isentropic Flow Relations	96
4.4.1	Property Ratios in Terms of Mach Number	97
4.4.2	Area Ratio in Terms of Mach Number	99
4.4.3	Impulse Function Ratio	101
4.4.4	Mass Flux in Terms of Mach Number	101
4.4.5	Mass Flux in Terms of Pressure Ratio	103
4.4.6	Mach Number and Area Ratio in Terms of Pressure Ratio	106
4.4.7	Use of Gas Tables and Charts	108
4.5	Supersonic Nozzles	108
4.6	Differential Equations Governing Flow with Area Change	110
4.6.1	Differential Form of Governing Equations	111
4.6.2	Differential Equations in Terms of Area Change	113
4.6.3	Influence Coefficients	114
4.7	Adiabatic Flow	114
4.7.1	Adiabatic Process in Mollier Diagram	115
4.7.2	Fluid Properties in Adiabatic Flow	116
4.7.3	Losses in Adiabatic Flow	117
	<i>Illustrative Examples</i>	117
	<i>Review Questions</i>	132
	<i>Problems</i>	134

5. FANNO FLOW

136-182

- 5.1 Introduction 136
- 5.2 Fanno Line 137
 - 5.2.1 Governing Equation 137
 - 5.2.2 Fanno Line in Mollier Diagram 138
 - 5.2.3 Limiting Condition for a Fanno Flow 141
 - 5.2.4 Choking Due to Friction 142
- 5.3 Fanno Relations for a Perfect Gas 145
 - 5.3.1 Temperature Ratio 145
 - 5.3.2 Pressure Ratio 146
 - 5.3.3 Density Ratio 147
 - 5.3.4 Velocity Ratio 148
 - 5.3.5 Stagnation Pressure Ratio 148
 - 5.3.6 Impulse Function Ratio 149
- 5.4 Change in Entropy Due to Friction 150
- 5.5 Dynamic Equation for Fanno Flow 151
 - 5.5.1 Friction Coefficient 151
 - 5.5.2 Pressure Drop Due to Friction 152
- 5.6 Differential Equations Governing Flow with Friction 153
 - 5.6.1 Differential Form of the Governing Equations 153
 - 5.6.2 Influence Coefficients 156
 - 5.6.3 Integration of the Equations 157
 - 5.6.4 Tables and Charts for Fanno Flow 160
- 5.7 Isothermal Flow in Long Constant Area Ducts 160
 - 5.7.1 Governing Equations 161
 - 5.7.2 Nature of Property Variations 163
 - 5.7.3 Property Ratios 164
 - 5.7.4 Change in Entropy 166
 - 5.7.5 Maximum Length of Duct 167

Illustrative Examples 168

Review Questions 180

Problems 181

6. RAYLEIGH FLOW

183-216

- 6.1 Introduction 183
- 6.2 Rayleigh Line 184
 - 6.2.1 Governing Equations 184
 - 6.2.2 Rayleigh Line in Mollier Diagram 185
 - 6.2.3 Simple Heating Process 186
 - 6.2.4 Simple Cooling Process 188
- 6.3 Significance of Maximum Entropy and Enthalpy State 189
 - 6.3.1 Choking in Rayleigh Flow 189
 - 6.3.2 State of Maximum Enthalpy 189
 - 6.3.3 *Mach Number at Maximum Entropy and Enthalpy* 190
 - 6.3.4 Region between Maximum Enthalpy and Entropy 194

6.4	Rayleigh Relations for a Perfect Gas	194
6.4.1	Pressure Ratio	195
6.4.2	Stagnation Pressure Ratio	196
6.4.3	Temperature Ratio	196
6.4.4	Stagnation Temperature Ratio	197
6.4.5	Density Ratio	198
6.4.6	Velocity Ratio	198
6.4.7	Change in Entropy Due to Heat Transfer	198
6.4.8	Working Tables and Charts	199
6.5	Amount of Heat Transfer	200
6.5.1	Choking Due to Heat Transfer	201
6.5.2	Maximum Possible Heat Addition	203
6.6	Differential Equations Governing Flow with Heat Transfer	204
6.6.1	Influence Coefficients for Simple Heat Transfer	204
6.6.2	Summary of Heating and Cooling Effects	205
	<i>Illustrative Examples</i>	206
	<i>Review Questions</i>	214
	<i>Problems</i>	215

7. SIMPLE FLOW WITH MASS ADDITION

217–233

7.1	Introduction	217
7.2	Effect of Mass Addition	218
7.2.1	Differential Equations Governing Mass Addition	218
7.2.2	Influence Coefficients	221
7.2.3	Summary of the Effect of Mass Addition	222
7.3	Equations for Property Ratios	222
7.3.1	Integration of Influence Equations	222
7.3.2	Property Ratios from the Basic Equations	223
7.3.3	Mollier Diagram Representation of Mass Addition	225
7.3.4	Tables and Charts	226
	<i>Illustrative Examples</i>	228
	<i>Review Questions</i>	233

8. GENERALISED ONE-DIMENSIONAL FLOW

234–245

8.1	Introduction	234
8.2	Formulation of Differential Equations	234
8.2.1	Conservation of Mass	234
8.2.2	Conservation of Momentum	235
8.2.3	Conservation of Energy	236
8.2.4	Other Equations	237
8.3	Method for Solving	238
8.3.1	Differential Equations in Matrix Form	238
8.3.2	Influence Coefficients	239
8.3.3	Method for Solution	241
8.4	General Features of Flow of a Perfect Gas	242
	<i>Review Questions</i>	245

9. NORMAL SHOCK WAVES

246-290

- 9.1 Introduction 246
- 9.2 Types of Waves in Compressible Flow 247
- 9.3 General Characteristics of the Normal Shock 248
 - 9.3.1 Governing Equations 249
 - 9.3.2 The Hugoniot Curve 250
 - 9.3.3 Normal Shock on Fanno and Rayleigh Curves 253
- 9.4 Normal Shock Equations for a Perfect Gas 255
 - 9.4.1 Prandtl-Meyer Equation 255
 - 9.4.2 Mach Number Downstream of Normal Shock 257
 - 9.4.3 Velocity and Density Ratio Across Normal Shock 258
 - 9.4.4 Pressure Ratio Across Normal Shock 258
 - 9.4.5 Temperature Ratio across Normal Shock 260
 - 9.4.6 The Stagnation Pressure Ratio 261
 - 9.4.7 Stagnation to Static Pressure Ratio 262
 - 9.4.8 Change in Entropy across Normal Shock 263
 - 9.4.9 Tables and Charts 265
- 9.5 Rankine-Hugoniot Relations 266
- 9.6 Weak and Strong Shocks 269
 - 9.6.1 Strength of Shock Wave 269
 - 9.6.2 Shock Condensation 271
- 9.7 Moving Normal Shock Wave 272
- Illustrative Examples* 273
- Review Questions* 288
- Problems* 289

10. OBLIQUE SHOCK WAVES

291-321

- 10.1 Introduction 291
- 10.2 Weak Compression and Expansion Waves 291
- 10.3 Compression Shock Wave and Expansion Fan 293
- 10.4 Analysis of Oblique Shock Wave 294
 - 10.4.1 Upstream and Downstream Velocity Triangles 294
 - 10.4.2 Governing Equations for Oblique Shock 296
 - 10.4.3 Variations in Flow Parameters 299
 - 10.4.4 Relation between Deflection Angle and Wave Angle 300
 - 10.4.5 Tables and Charts for Oblique Shock 302
 - 10.4.6 Other Oblique Shock Relations 304
- 10.5 Mach Lines 306
- 10.6 Expansion of Supersonic Flow 307
 - 10.6.1 Analysis of Prandtl-Meyer Flow 308
 - 10.6.2 The Prandtl-Meyer Angle 311
- Illustrative Examples* 314
- Review Questions* 320
- Problems* 321

11. FLOW THROUGH NOZZLES AND DIFFUSER

322–361

- 11.1 Introduction 322
- 11.2 Operation of Nozzles Under Varying Pressure Ratio 322
 - 11.2.1 Convergent Nozzle 322
 - 11.2.2 Convergent-Divergent Nozzle 325
- 11.3 Under Expansion and Over Expansion in Nozzles 330
 - 11.3.1 Under Expansion 330
 - 11.3.2 Over Expansion 330
- 11.4 Losses in Nozzles 333
 - 11.4.1 Nozzle Efficiency 333
 - 11.4.2 Velocity Coefficient and Discharge Coefficient 335
 - 11.4.3 Actual Exit Mach Number 336
 - 11.4.4 Change in Entropy 337
- 11.5 Performance of Diffusers 339
 - 11.5.1 Total Pressure Recovery Factor 340
 - 11.5.2 *Isentropic Diffuser Efficiency* 341
 - 11.5.3 Kinetic Energy Efficiency 342
- 11.6 Subsonic and Supersonic Air Intakes 343
 - 11.6.1 Internal Compression Subsonic Intakes 343
 - 11.6.2 External Compression Subsonic Intakes 344
 - 11.6.3 Supersonic Intakes 344
- 11.7 Wind Tunnel 346
 - 11.7.1 Blow Down Wind Tunnel 347
 - 11.7.2 Atmospheric Entry Wind Tunnel 347
 - 11.7.3 High Enthalpy Wind Tunnel 347
 - 11.7.4 Continuous Flow Wind Tunnel 348
- Illustrative Examples* 350
- Review Questions* 359
- Problems* 360

12. MEASUREMENTS IN COMPRESSIBLE FLOW

362–397

- 12.1 Introduction 362
- 12.2 Measurement of Temperature 363
 - 12.2.1 Inserting Probe into the Flow 363
 - 12.2.2 Using Near Wall Temperature 365
 - 12.2.3 Stagnation Temperature Probe 366
- 12.3 Measurement of Pressure 367
 - 12.3.1 Static Pressure 368
 - 12.3.2 Stagnation Pressure 369
 - 12.3.3 Prandtl Pitot Static Probe 369
 - 12.3.4 Kiel Probe 370
 - 12.3.5 Pitot Tube for Supersonic Flow 372
- 12.4 Measurement of Flow Velocity and Mach Number 374
 - 12.4.1 Measurement in Subsonic Flow 374
 - 12.4.2 Measurement in Supersonic Flow 374
 - 12.4.3 Hot Wire Anemometer 376

12.5	Quantitative Estimation of Flow Direction	380
12.5.1	Claw Type Direction Probe	381
12.5.2	Cobra Probe	381
12.5.3	Wedge Probe	381
12.6	Measurement of Flow Rate	382
12.6.1	Obstruction Meters	382
12.7	Flow Visualization	384
12.8	Density Variation Techniques	386
12.8.1	Principle of Optical Instruments	387
12.8.2	Schlieren Apparatus	388
12.8.3	Shadowgraph	390
12.8.4	Interferometer	391
12.9	Laser Velocimeters	393
	<i>Review Questions</i>	395

13. AIR BREATHING PROPULSION

398-469

13.1	Introduction	398
13.2	Aircraft Propulsion Engines	399
13.2.1	Propeller Engine	399
13.2.2	Turbojet Engines	399
13.2.3	Turboprop and Turboshaft Engines	405
13.2.4	Turbofan Engine	405
13.2.5	Ramjet Engine	406
13.2.6	Pulse Jet Engine	409
13.3	Thermodynamic Cycle	410
13.3.1	Basic Brayton Cycle	411
13.3.2	Open Brayton Cycle for Propulsion Systems	415
13.3.3	Diffusion Process	417
13.3.4	Compression Process	419
13.3.5	Combustion Process	420
13.3.6	Expansion Process in Turbine	421
13.3.7	Expansion in the Nozzle	422
13.4	Propulsion Performance Parameters	423
13.4.1	General Thrust Equation	424
13.4.2	Thrust of Turbojets	426
13.4.3	Thrust of Ramjet	427
13.4.4	Effective Jet Velocity	427
13.5	Thrust, Power and Fuel Consumption	427
13.5.1	Jet Power or Thrust Power	427
13.5.2	Propulsive Power	428
13.5.3	Specific Thrust and Specific Impulse	428
13.5.4	Specific Fuel Consumption	429
13.5.5	Thrust Coefficient	429
13.6	Energy Flow and Efficiency	429
13.6.1	Energy Flow in Propulsion Engines	429
13.6.2	Efficiency Considerations	430

13.6.3	Propulsive Efficiency	431
13.6.4	Speed Ratio	432
13.6.5	Thermal Efficiency	433
13.6.6	Overall Efficiency	433
13.7	Comparison of Propulsion Systems	434
13.7.1	Propeller Engine	434
13.7.2	Turboprop Engine	434
13.7.3	Turbojet Engine	435
13.7.4	Turbofan Engine	436
13.7.5	Ramjet Engine	436
13.7.6	Pulsejet Engine	437
	<i>Illustrative Examples</i>	438
	<i>Review Questions</i>	466
	<i>Problems</i>	468

14. ROCKET PROPULSION

470-525

14.1	Introduction	470
14.2	Chemical, Nuclear and Electric Propulsion	471
14.3	Rocket Propulsion Parameters	471
14.3.1	Thrust Equation	471
14.3.2	Energy Flow and Efficiencies	473
14.3.3	Specific Impulse and Total Impulse	475
14.3.4	Effective Jet Velocity	476
14.3.5	Specific Propellant Consumption	476
14.3.6	Mass Flow Coefficient and Thrust Coefficient	477
14.3.7	Characteristic Velocity	478
14.3.8	Mass Ratio and Propellant Mass Fraction of a Rocket System	478
14.4	Gas Dynamic Relationships for the Rocket Engine	479
14.4.1	Nozzle Flow Parameters	480
14.4.2	Area Ratio for Complete Expansion	481
14.4.3	Exit Velocity of Jet	481
14.5	Design Parameters for Rocket Engine	481
14.5.1	Mass Flow Coefficient	482
14.5.2	Ideal Thrust Equation and Thrust Coefficient	482
14.5.3	Characteristic Velocity	483
14.6	Types of Chemical Rocket Engines	484
14.6.1	Solid Propellant Rocket Engine	484
14.6.2	Liquid Propellant Rocket Engines	486
14.6.3	Hybrid Rocket Engine	490
14.7	Propellants	491
14.7.1	Solid Propellants	491
14.7.2	Liquid Propellants	492
14.8	Combustion of Solid Propellants	494
14.8.1	Linear Burning Rate	494
14.8.2	Propellant Area Ratio and Pressure Limit	495
14.8.3	Regressive, Neutral and Progressive Burning	495
14.8.4	Grain Designs for Restricted and Unrestricted Burning	496

14.9	Combustion of Liquid Propellants	496
14.9.1	Injection of Liquid Propellant	496
14.9.2	Ignition	499
14.10	Other Non-Air Breathing Propulsion Engines	500
14.10.1	Nuclear Rocket Engine	500
14.10.2	Electrical Rocket Engines	501
14.11	Flight Performance	503
14.11.1	The Rocket Equation	504
14.11.2	Altitude Gain During Vertical Flight	506
14.11.3	Multi-stage Rockets	507
14.11.4	Escape Velocity	507
	<i>Illustrative Examples</i>	508
	<i>Review Questions</i>	521
	<i>Problems</i>	523

APPENDIX A1	Isentropic Flow Tables for Perfect Gas ($\gamma \approx 1.4$)	527
APPENDIX A2	Fanno Flow Tables for Perfect Gas ($\gamma = 1.4$)	531
APPENDIX A3	Isothermal Flow Tables for Perfect Gas ($\gamma = 1.4$)	536
APPENDIX A4	Rayleigh Flow Tables for Perfect Gas ($\gamma \approx 1.4$)	539
APPENDIX A5	Simple Mass Addition Tables for Perfect Gas ($\gamma \approx 1.4$)	544
APPENDIX A6	Normal Shock Tables for Perfect Gas ($\gamma \approx 1.4$)	548
APPENDIX A7	Oblique Shock Tables and Charts for Perfect Gas ($\gamma = 1.4$)	551
APPENDIX A8	Prandtl-Meyer Flow Tables for Perfect Gas ($\gamma = 1.4$)	565
APPENDIX A9	Table of Standard Atmosphere	568